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PRELIMINARY DEVELOPMENT OF ELECTRODES FOR AN ELECTRIC-ARC WIND TUNNEL

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SUMMARY

Two electrode configurations were tested in an electric-arc wind tunnel at the NASA Lewis Research Center. The results indicated approximately the same heat-loss rate per unit of arc power input for each of the configurations. Measured heat-loss rates were on the order of 40 percent of the arc power input. Nearly all this loss occurred at the anode. The power input and arc current limitations of the electrodes appear to be the critical design factors. Up to now, the maximum power to the stream has been 115 kilowatts with a cooled tungsten cathode and a cooled cylindrical anode incorporating a magnetic field. The maximum power input to this anode could not be established with the cooled tungsten cathode because cathode failures occurred at a gross power level of approximately 175 kilowatts. It was necessary to use a graphite cathode to seek the limitation of the anode. The results indicated that the anode limitation was primarily a function of arc current rather than power input. The anode was successfully operated at a power of 340 kilowatts at 1730 amperes; however, the anode failed with a power input of 324 kilowatts and a current of 2140 amperes. The magnetic flux density at the time of failure was 0.32 weber per square meter, or 3200 gauss. The graphite cathode was used only to establish the anode limitation; further investigation of graphite cathodes was discontinued because of the large amount of stream contamination associated with this type of electrode.

INTRODUCTION

In order to solve many of the problems encountered during atmospheric reentry of ballistic or satellite vehicles, simulation of the reentry environment in a ground test facility is desirable. One method of creating such an environment is by using a hypersonic electric-arc wind tunnel. Such a facility can simulate the stagnation enthalpy and pressure occurring behind the normal shock of a reentry body and, therefore, provide information for the study of reentry heating problems.

An electric-arc wind tunnel in which the working fluid is heated in a direct-current electric arc has been constructed at the NASA Lewis Research Center. This tunnel has a 4-inch-diameter test section and is designed to operate at a maximum power input of 200 kilowatts to the gas stream and a stagnation pressure of 2 atmospheres. Cooled electrodes are used in order to reduce the contamination of the gas stream. In the majority of tests, nitrogen was used as the working fluid. Nitrogen is often a satisfactory working fluid in reentry heat-transfer experiments because its transport properties resemble the transport properties of air; however, in certain studies it is desirable to determine the effects of the reaction of air with the material of the model. For this reason, plans are being formulated to inject oxygen downstream of the electrodes so that the fluid in the nozzle can be made to simulate the atmosphere at any desired altitude.

In the construction of the arc tunnel, the major problem is the development of electrodes capable of supplying the design power to the gas stream. There is a very close relation between the electrode design and the cooling requirements. The present study is aimed at the development of an electrode configuration suitable for wind-tunnel application and the determination of the cooling techniques that will permit operation at the highest possible power level. The purpose of this report is to present the preliminary results of the electrode development program with emphasis on the electrode configuration, corresponding heat loss, and operation limitation.

SYMBOLS

$\overline{B}$	magnetic flux density vector, webers/sq meter
C_p	specific heat at constant pressure, Btu/lb$_m$
$\overline{F}$	force per unit volume vector, newtons/cu meter
h_0	stagnation enthalpy, Btu/lb$_m$
$\overline{J}$	current density vector, amp/sq meter
$\dot{m}$	mass-flow rate, lb$_m$/sec
P	total arc power input, Btu/sec
Q	heat-loss rate, Btu/sec

T	temperature, $^{\circ}F$

Subscripts:

m	mass
n	nitrogen
w	water

APPARATUS AND INSTRUMENTATION

Apparatus

Arc tunnel. - The components of the arc tunnel are illustrated in figure 1. The facility is made up of the generators, electrodes, supersonic nozzle, test section, and diffuser. The supersonic nozzle is conical with a 1/2-inch throat and a 4-inch exit diameter; the test section is 12 inches long and 4 inches in diameter. Both the nozzle and test section are cooled with water. The diffuser is lined with graphite and does not require liquid cooling. Power regulation is achieved by varying the supply voltage. Two generators, each providing 250 volts, are connected in series to supply a maximum potential of 500 volts at 6000 amperes. A water-cooled ballast resistor of 0.25 ohm is used to stabilize the arc. The arc is started with a 0.010-inch brass wire across the electrodes.

Electrodes. - Two anode configurations were tested with the same general type of cathode, which consists of a 3/4-inch copper tube with a thoriated tungsten tip (fig. 2). Cooling water is directed to the tip through a 1/4-inch copper tube. The cathode rod is enclosed in a $1\frac{1}{4}$-inch sleeve that provides a passage for the flow of nitrogen. It was necessary to modify the geometry of the cathode tip for certain operating conditions; these modifications are discussed in another section.

Provision was made for the injection of secondary air at the anode; however, this feature was not incorporated in any of the tests described herein.

The convergent-divergent (CD) anode, as shown in figure 3, is a water-cooled subsonic nozzle with a throat diameter of 3/4 inch. The arc, which is established by the vaporization of the starting wire, is blown into the nozzle by the gas flow. The nozzle stabilizes the arc by constricting the arc at the throat. The constriction produces magnetic forces that further contract the arc (ref. 1). In addition, the cold nozzle surface chills the outer part of the arc, which also limits the diameter of the arc.

After passing through the throat, the arc spreads out fairly uniformly over the divergent section. Because of this behavior, it would appear feasible to arc directly into the flow nozzle of the supersonic tunnel; however, tests showed that the resulting flow is very unsteady. For this reason, the CD anode is run subsonically, and a separate flow nozzle is used.

Figure 4 shows the sleeve anode, which uses a different method of arc stabilization. A magnetic field is used to rotate the arc and thus distribute the discharge over the periphery of the anode sleeve. Nitrogen, which passes relatively slowly through the sleeve, is uniformly heated by the rapidly rotating arc. Although the arc is not confined as for the CD anode, it is directed around the anode surface by the magnetic field and in this sense is stabilized. The field, which is longitudinal in direction, is produced by a solenoid coil of water-cooled copper tubing. The forces on the arc are given by the usual formula:

$$\overline{F} = \overline{J}x\overline{B}$$

By assuming the current to be normal to the anode surface, the force is seen to be tangential.

The main arc current passes through this coil. The series connection is believed to aid the stability since an increase in current, which might result from the vaporization of anode material at a local hot spot, will cause an increase in the rotating force. For this arrangement the force varies as the square of the current.

The nitrogen gas is heated as it advances through the rotating arc. This rotational motion is transferred to the gas so that enthalpy fluctuations are smoothed; however, the major advantage is the distribution of the heat load over a large area of the anode. This is very important since the anode heat loss is a sizable fraction of the total power input. For this reason the sleeve anode can handle much more power than the CD anode.

Instrumentation

Flow. - The primary flow of nitrogen was measured by means of a calibrated orifice. Bottled nitrogen was used in all the tests.

The cooling water was measured by turbine-type flow transducers whose output is read on a frequency meter. The coolant flow rate was subsequently used in the estimation of various heat losses.

Temperature and enthalpy. - The temperature of the gas stream was not measured. Rather, stagnation enthalpy was estimated from a knowledge of the power supplied to the stream and mass-flow rate. The temperatures of the cooling water were measured with conventional thermocouples.

Pressure. - A 1/16-inch-diameter pressure tap located at the downstream end of the anode was used to measure the stagnation pressure. This pressure was obtained from a mercury manometer and also from a compound pressure gage.

Electrical measurements. - A 4000-ampere 50-millivolt shunt was used for the arc current measurement; this voltage was read on a suitable millivolt meter. The arc voltage was read directly. A dual-beam direct-coupled oscilloscope was used to observe simultaneous voltage and current fluctuations. The arc power input was measured with a wattmeter.

PROCEDURE

Heat-Loss Rates

Heat-loss rates were obtained by the simple calorimetric technique, wherein the temperature rise of the coolant across the electrode and the coolant flow rate must be known. The heat-loss rate of a component may be expressed as

$$Q = \dot{m}_W \Delta T C_p \tag{1}$$

Stagnation Enthalpy

Stagnation enthalpy was computed from a knowledge of the nitrogen mass-flow rate and the power into the stream as follows:

$$h_O = \frac{P - Q}{\dot{m}_n} \tag{2}$$

Since the heat-loss rate of the anode was much larger, the losses of the other components were generally neglected in computing the stagnation enthalpy.

Stagnation Pressure

Stagnation pressures were measured directly in the majority of tests.

Temperature

Although the temperature of the gas stream was not measured directly, values of bulk temperature were estimated from a knowledge of stagnation pressure and enthalpy. The enthalpy-temperature chart for nitrogen in thermodynamic equilibrium in reference 2 was extended to include values of enthalpy and pressure obtained with the arc tunnel. The extension was based on data from reference 3.

RESULTS

Heat-Loss Rates

The anode heat-loss rate, as computed from equation (1), is plotted as a function of arc power input in figure 5. Data for each of the configurations appear to correlate in a linear mode; this indicates anode losses of approximately 40 percent of the arc power input. The data were not corrected for differences in mass-flow rate because a suitable parameter has not been derived. Much of the scatter in the data can be attributed to these uncorrected differences.

Cathode losses are on the order of 4 percent of the arc power input, as shown in figure 5. The losses remain nearly constant over the complete range of power input.

Electrode Limitations

Although the current appears to be the limiting factor on anode life, it is convenient to discuss the results in terms of power since the voltage does not change appreciably over a wide range of operating conditions for a given electrode configuration. The power limitations of the electrodes are indicated in figure 5. The CD anode is limited to a power input of about 100 kilowatts, of which approximately 60 kilowatts are supplied to the gas stream.

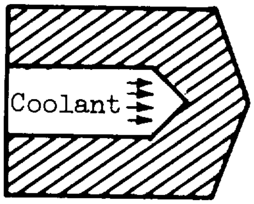
At higher powers, burnout of the anode occurs slightly downstream of the throat. This failure occurs when the cooling becomes inadequate; therefore, it can be delayed by using an anode material with a high thermal conductivity, by using a thin wall, and by using a high-velocity high-pressure coolant flow. The local heat load can be reduced by using a material such as nickel, which is less susceptible to the concentration of the arc at a small spot. The CD anode of figure 3, which has a 1/8-inch copper wall, failed at current above 800 amperes for a cooling-water velocity of 24 feet per second and a pressure of 55 pounds per square inch. This limit could be increased by using a nickel-plated surface and by varying the nozzle geometry; however, the sleeve anode of figure 4 appears to have inherently better power-handling capabilities.

The cooling problems of the sleeve anode are essentially the same as for the CD anode except that the heat load is spread out over a larger area. From the marks made by the arc on the anode surface, the typical path of the discharge is a portion of a helix. Apparently the arc then restrikes elsewhere.

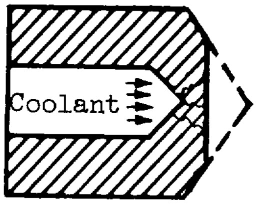
The maximum power that the sleeve anode could handle could not be determined when the tungsten cathode of figure 2 was used. (The power limitation of the cathode is discussed later.) For this reason a graphite cathode was used to fix these limits. As stated previously, burnout of the anode appears to depend more on the current than on the arc power. For example, the number 2 anode of figure 4 was successfully operated at 340 kilowatts and a current of 1730 amperes. However, at 324 kilowatts and 2140 amperes it failed. This anode was nickel-plated; an unplated sleeve anode of the same size failed at 2070 amperes. The magnetic field strength of the coil was about 236,000 ampere turns per meter; this corresponds to a flux density of approximately 3000 gauss. About 15 turns of 5/16-inch copper tubing were used. No overheating of the tubing was observed at maximum current for a cooling-water pressure of 100 pounds per square inch.

The graphite cathode was not considered desirable because of the large amount of gas stream contamination that it produced. The amount of contamination, determined by weighing the cathode, ranged up to several percent. For this reason development of the nonconsumable cathode is continuing. (The feasibility of using graphite electrodes has not been completely disregarded, for recently tests have been conducted in which the contamination in the gas stream from a carbon cathode - metallic anode configuration was as low as 2 percent at a power input of 130 kilowatts (ref. 4).)

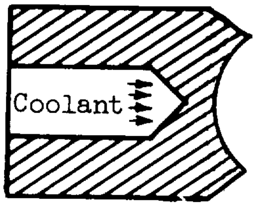
Difficulties arise with the 3/4-inch tungsten cathode when the current is approximately 1000 amperes or greater. Severe erosion and ablation cause the cathode to fail almost immediately. The following sketches illustrate the nature of these failures:



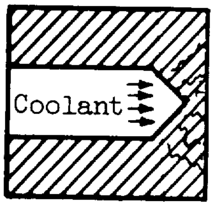
(a)



(b)



(c)



(d)

Sketch (a) illustrates the cathode as originally designed. This configuration was used successfully at currents as high as 1000 amperes. At higher currents, the cathode began to erode and ablate, and assumed the geometry of sketch (b). In an attempt to increase the area available for arc attachment, the pointed tip was replaced by the hollow tip shown in sketch (c); however, this was not successful. After 30 minutes of operation at a current of approximately 1200 amperes, the cathode of sketch (c) transformed to the plane-faced configuration of sketch (d). Other configurations, including a hemisphere and a paraboloid, resolved into this same contour. A severe temperature gradient was imposed on all these configurations because of the extreme depth of the coolant passage. It is believed that the thermal shock associated with this temperature gradient causes cracking of the tip and results in leakage of the coolant and cathode failure. Future designs will be modified by eliminating the counterbored coolant passages in the tip.

Although a systematic investigation of the effects of pressure and mass-flow rate has not been conducted, a few generalities can be stated. Increasing the pressure increased the tendency of anode burnout, while increasing the mass-flow rate improved the service life of the anode. Similar effects were noted with the cathode except at very low pressures where sputtering of the tungsten occurred. A few runs were made with air as the working fluid. The presence of oxygen did not have an adverse effect on the anode; however, the cathode had to be well shielded from the oxygen.

Stagnation Enthalpy and Temperature

Stagnation enthalpies were calculated from equation (2) and plotted as a function of arc power input in figure 6. Mass-flow variations account for the scatter in the data. Nitrogen mass-flow rates ranged from 0.005 to 0.015 pound per second. Maximum stagnation enthalpies of 9800 and 18,500 Btu per pound were obtained with the CD and sleeve anodes, respectively.

For a stagnation pressure of 0.5 atmosphere and a stagnation enthalpy of 12,000 Btu per pound, the bulk temperature of the gas is approximately 12,500° R.

Stagnation Pressure

Measured values of stagnation pressure are plotted as a function of the arc power input in figure 7. Of course, the stagnation pressure is also a function of the mass-flow rate. The majority of tests were conducted with stagnation pressures on the order of 0.5 atmosphere. Stagnation pressures were not measured for several of the runs with the sleeve anode. An exhaust pressure of approximately 0.1 atmosphere was maintained in all the runs.

CONCLUSIONS

Experimental tests of two electrode configurations in an electric-arc wind tunnel indicate the following conclusions and results:

1. Application of a magnetic field about the anode looks attractive from the standpoint of arc stabilization, power input, and gas mixing characteristics.

2. The tungsten cathode must be modified in some manner in order to obtain the design power of 200 kilowatts to the stream.

3. Anode cooling requirements accounted for a loss of approximately 40 percent of the gross arc power input. The 60-percent electrode efficiency appeared to be nearly constant for the entire range of operating conditions.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 15, 1959

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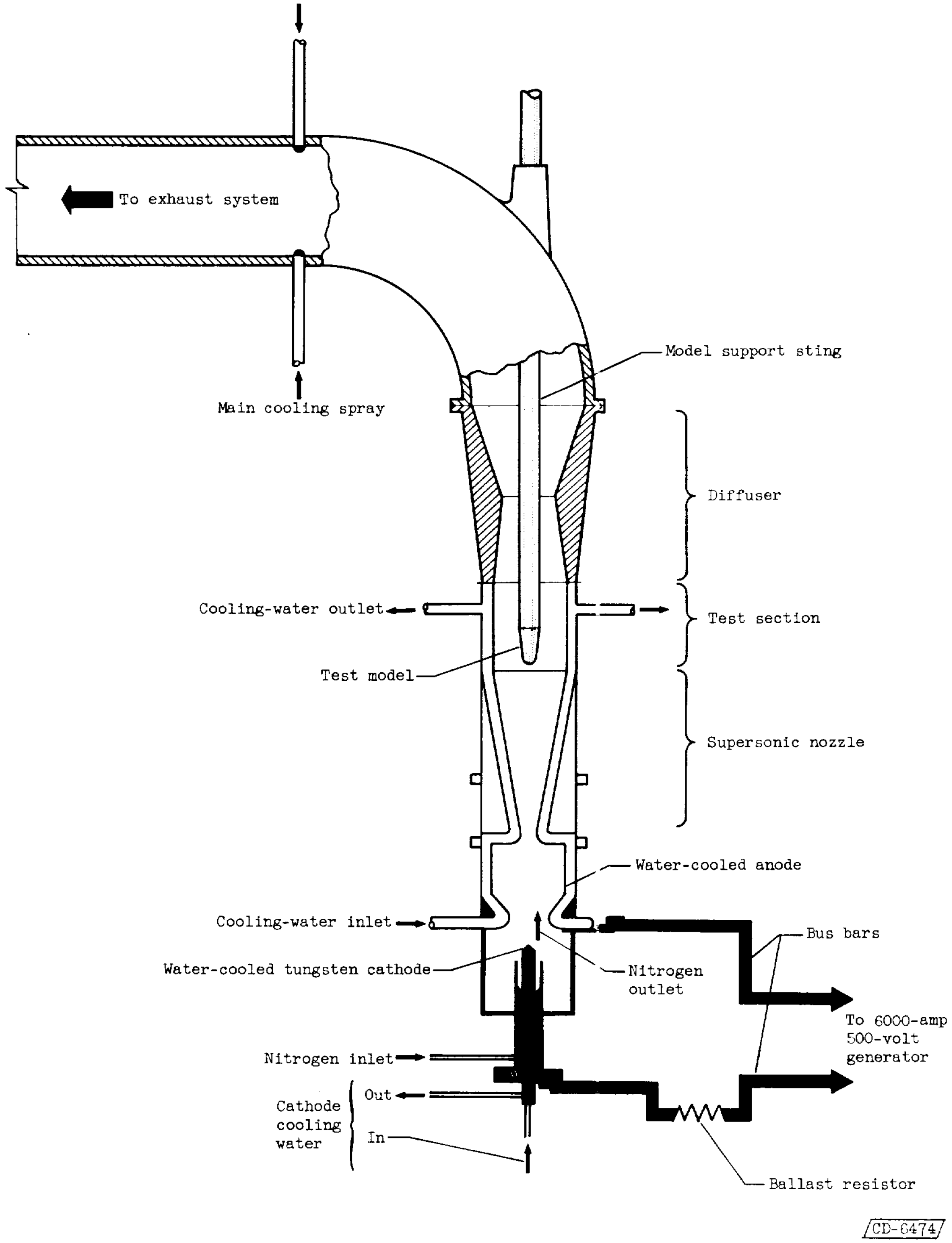


Figure 1. - Electric-arc wind tunnel.

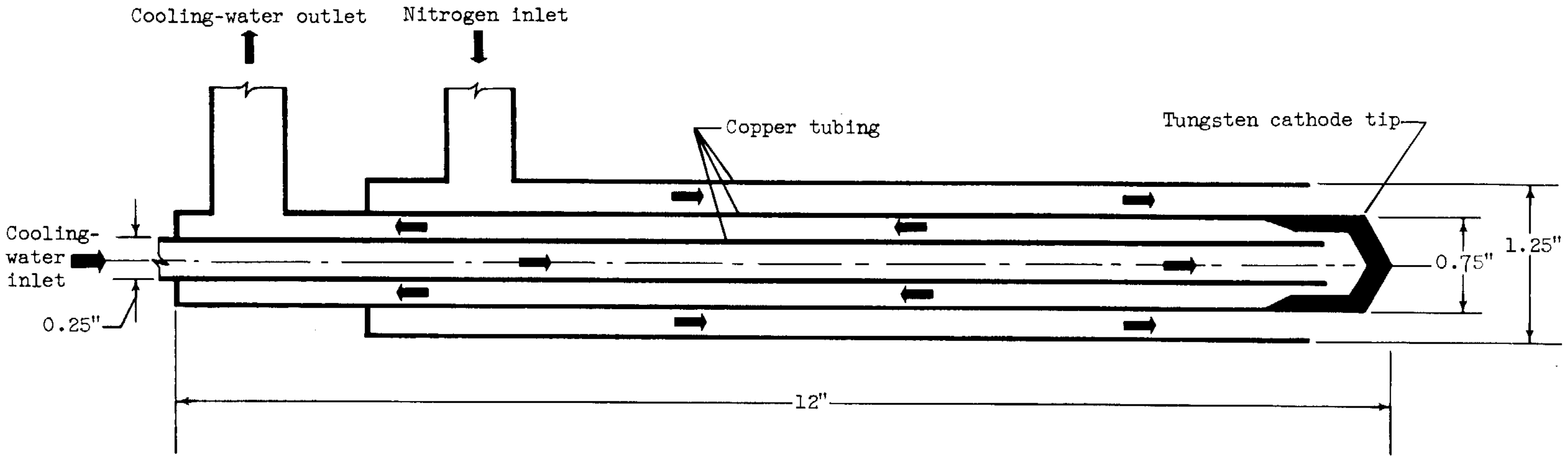


Figure 2. - Cathode.

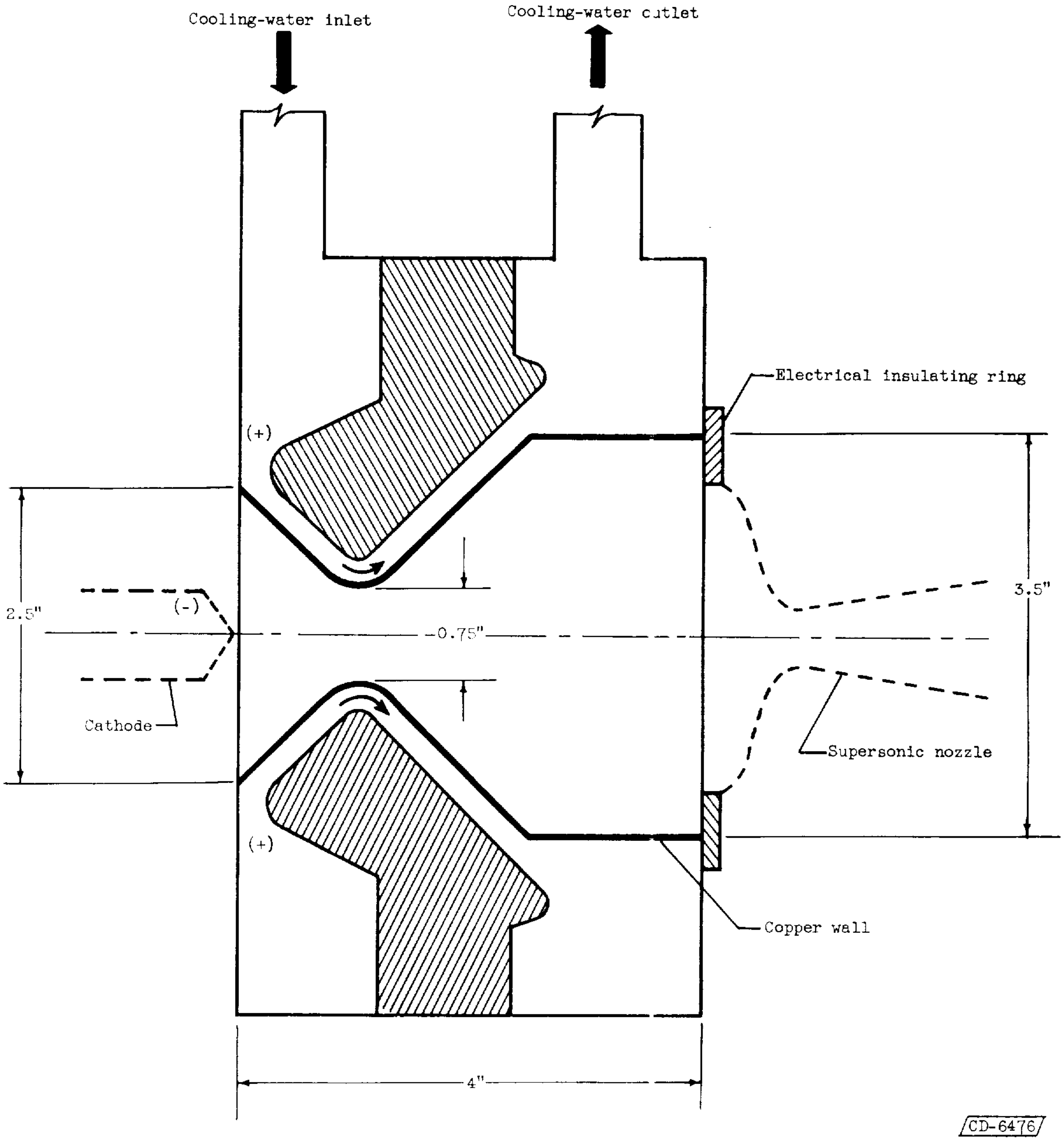
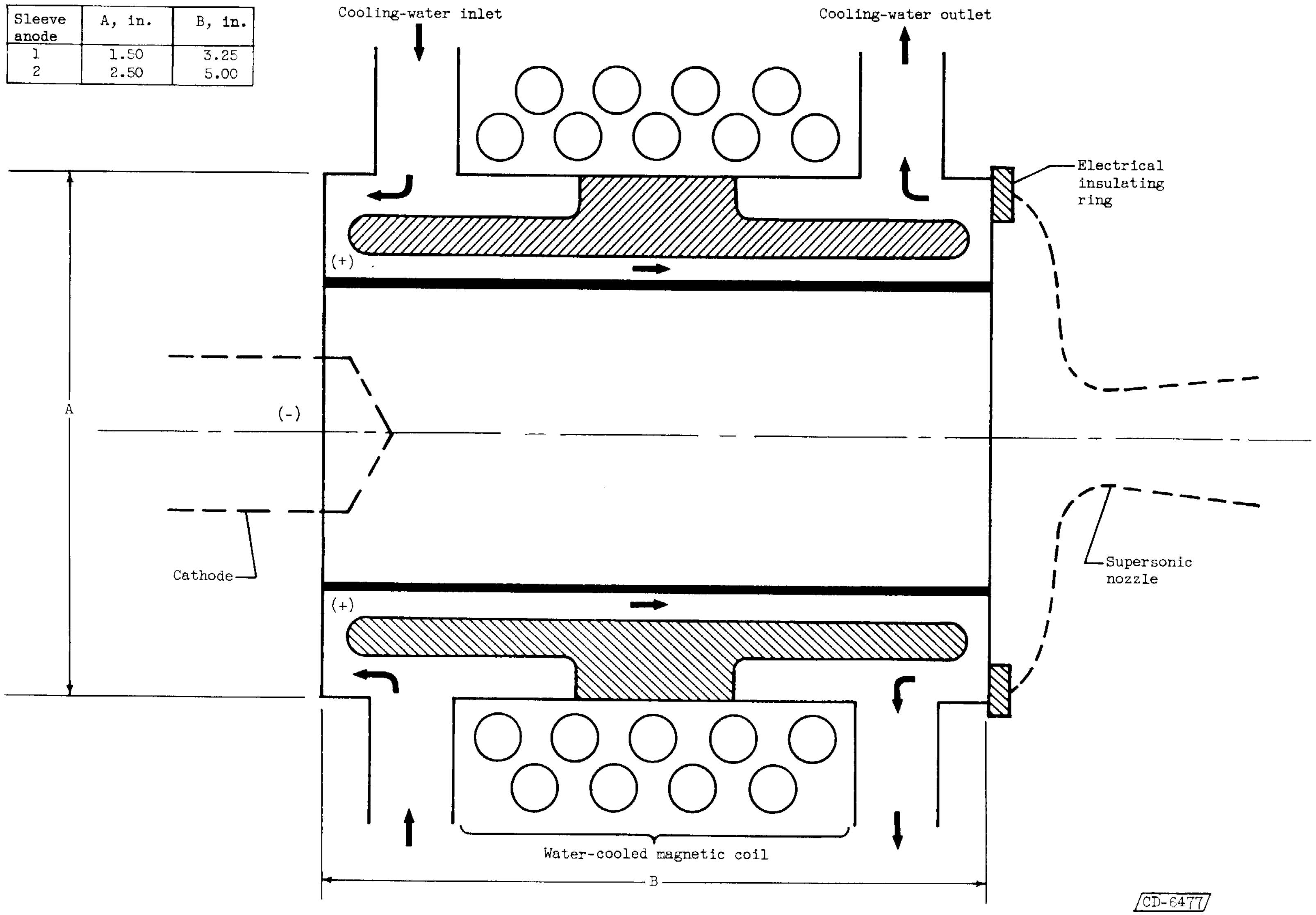


Figure 3. - Convergent-divergent anode.



Sleeve anode	A, in.	B, in.
1	1.50	3.25
2	2.50	5.00

Figure 4. - Sleeve anode.

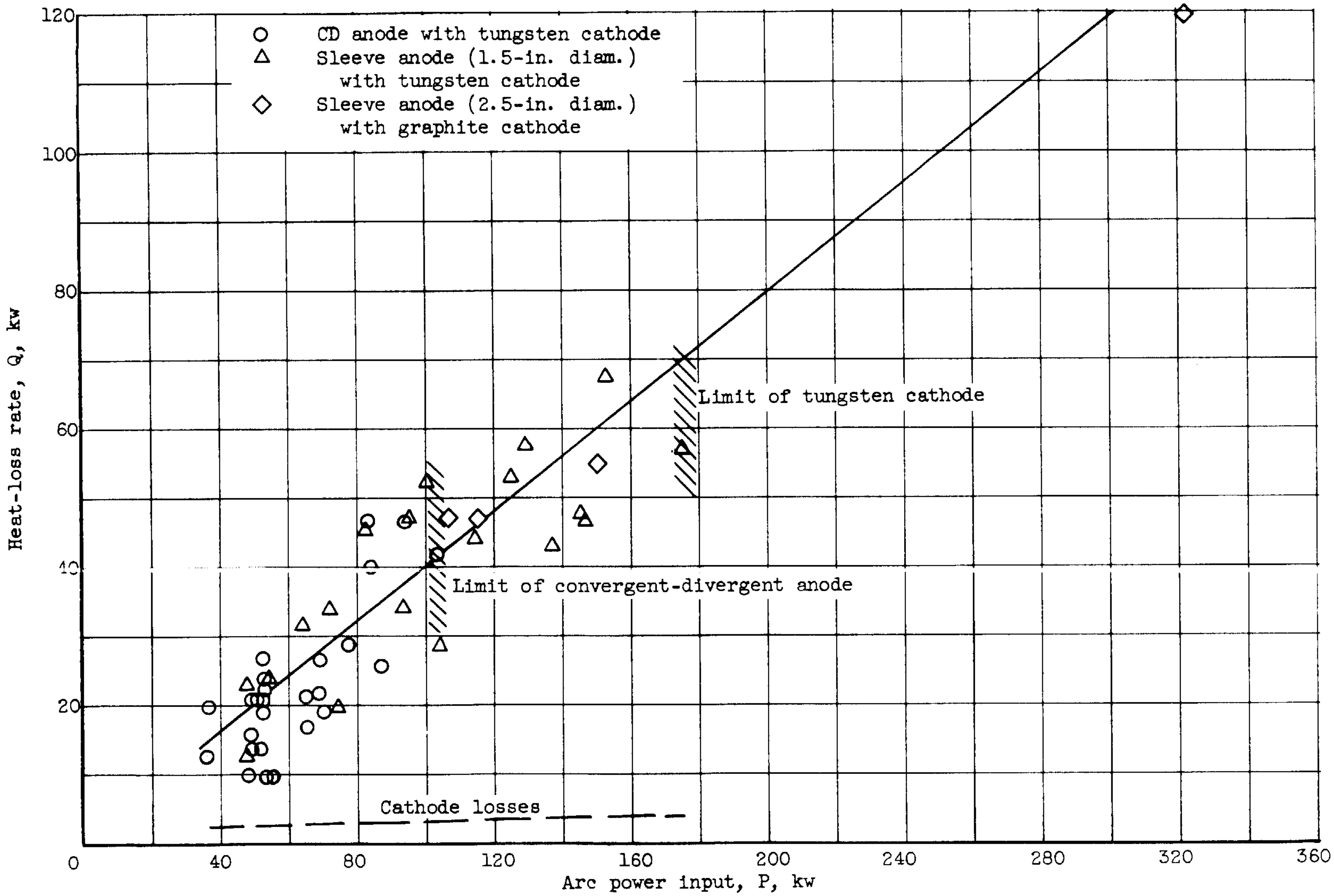


Figure 5. - Variation of heat-loss rate with arc power input.

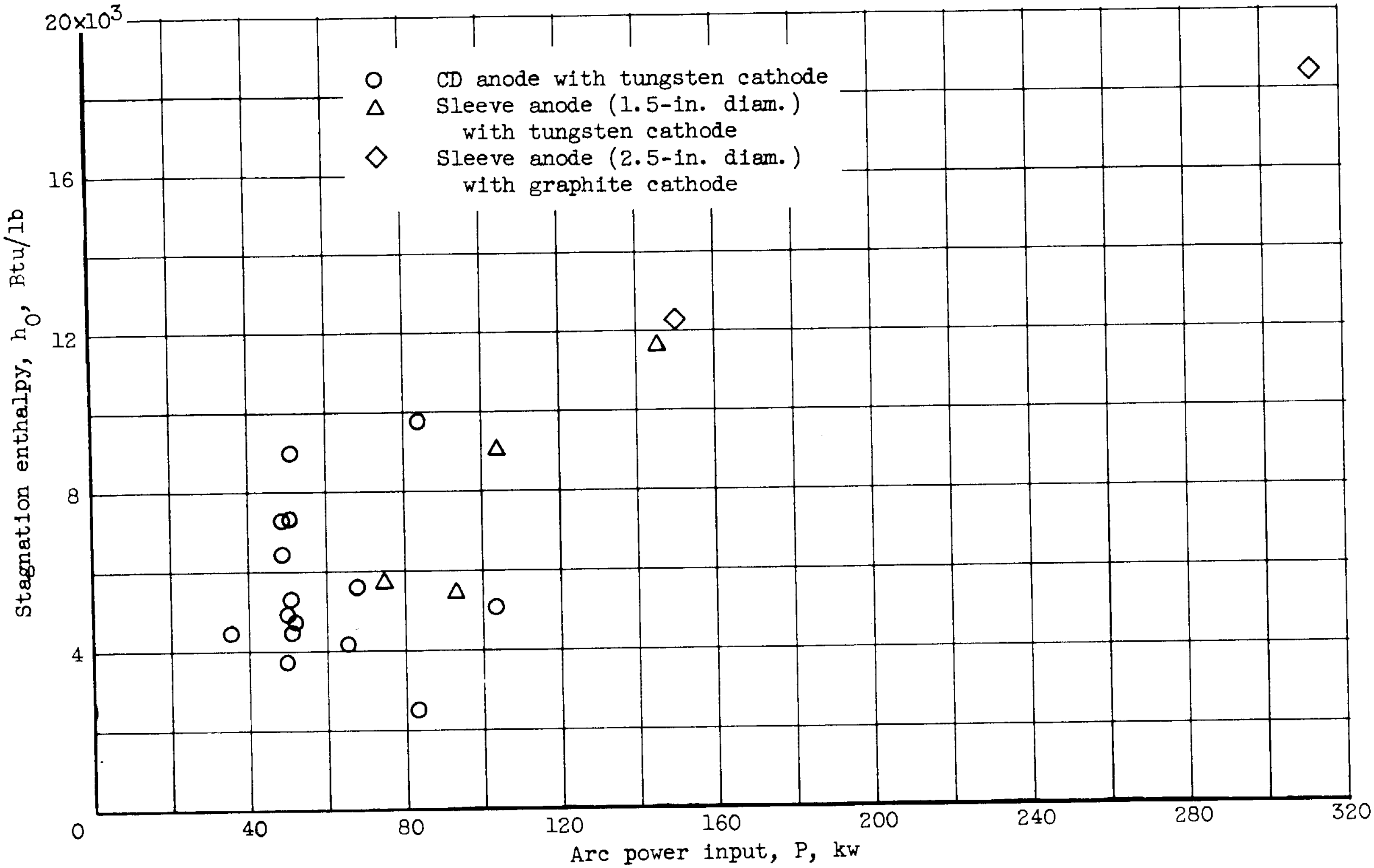


Figure 6. - Stagnation enthalpies obtained with convergent-divergent and sleeve anodes.

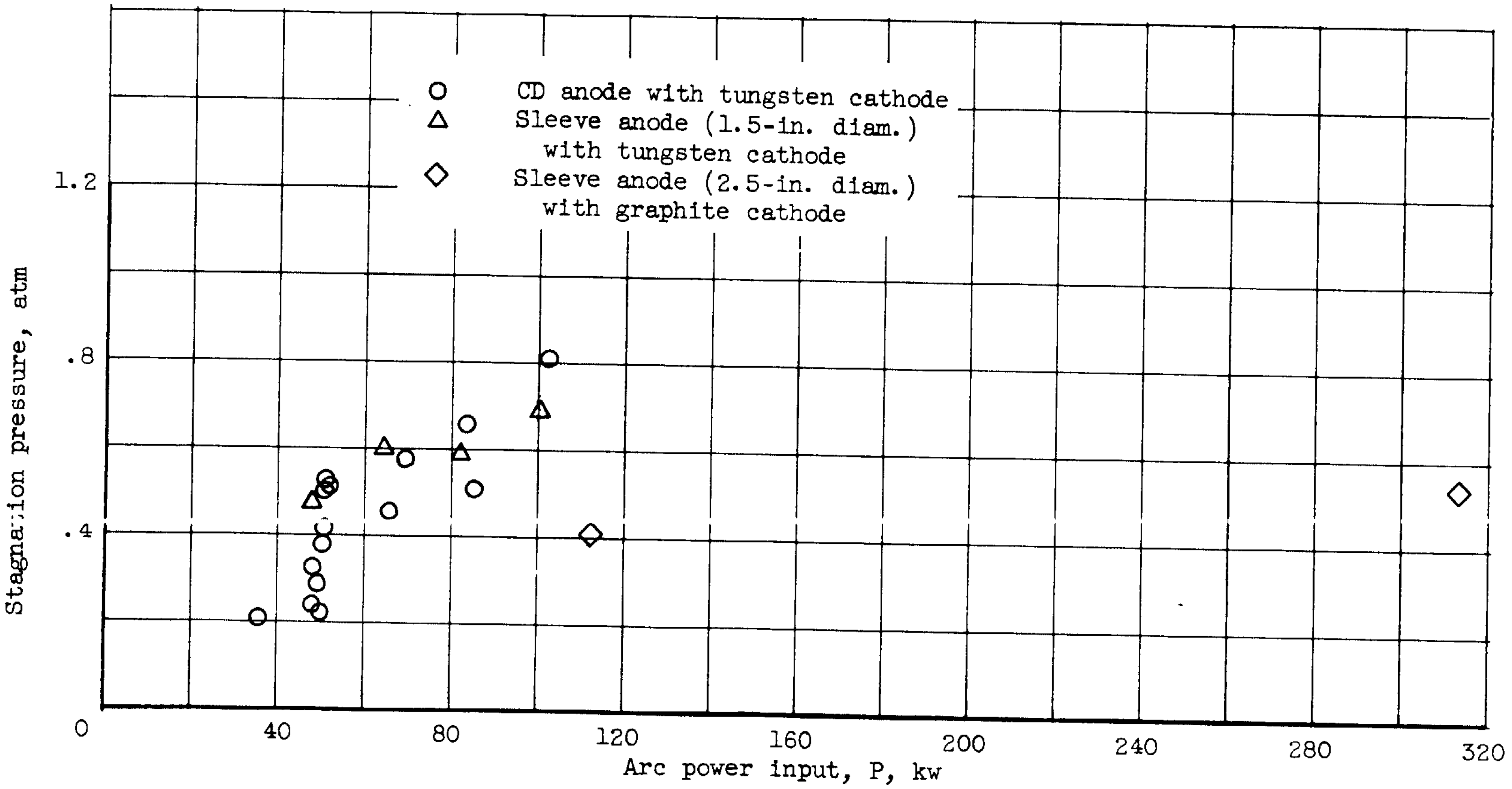


Figure 7. - Stagnation pressures obtained with convergent-divergent and sleeve anodes.

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